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Geodesy and Alignment Concepts for the Fermi Main Injector

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GEODESY AND ALIGNMENT CONCEPTS FOR THE FERMILAB MAIN INJECTOR

1. PRECISE "SURFACE NETWORK" SURVEY

Faced with continuing demands for higher precision in the construction of the new 150 GeV particle accelerator, designated the Fermilab Main Injector (FMI), the Alignment, Survey and Geodesy Group has carried on its search for improvements in the geodetic control of the tunnel excavation and the installation of the machine elements. Achieving greater precision is made possible because of more detailed analysis of the methods employed and of the measurements themselves, because of improvements in the technology of instrument manufacture, and because of a reevaluation of all possible perturbing influences on the final accuracy.

The search for accuracy in geodetic metrology demands that the processing of the data always remains rigorous, and takes into account any factors which can effect the exactness of the measurements or of the results.

Major changes in geodetic concepts have been introduced in designing the FMI. The computation of the theoretical coordinates of the machine has required increasingly precise considerations of the geometry of the earth. Even if the non-homogeneity of the earth and the surrounding topography do not change dramatically and give rise to major distortions of the gravity equipotential surfaces, determining the exact spatial geometric interrelationship between the Tevatron and the Main Injector remains critical and demands a thorough investigation of the geoid model. Both rings lie in different planes that are perpendicular to the local gravity vectors; one at the center of the Tevatron, the other is displaced from the geometric center of the Main Injector. Another reason for defining a precise geoid model is to determine the magnitude of corrections that will compensate for deflections from the vertical.

The initial geodetic references for the construction and positioning of the FMI will derive from a precise surface network. The FMI absolute positioning tolerances and the circumference requirements specifications require an extensive, combined Global Positioning System (GPS), terrestrial, and astrogeodetic survey. This master control network is composed of 35 permanent pillar type monuments that globally cover the Fermilab site and yields 2 mm positional accuracy.

The FMI control network is represented by nine of the 35 master control points. Eight points surround the FMI track while one is located at the center, this configuration forming a polygon. From the point of view of the strength of the network, this areal geometric configuration is the best because the random errors propagate very slowly and rather uniformly. In defining the mathematical model of the space in which we take measurements and perform data analysis, we employ the Geodetic Reference System 1980 ellipsoid (GRS 80) in conjunction with the local geoid model. Combining GPS vectors with precise leveling observations and GEOID 93 model undulations provides an independent control of the local geoid model.

The complexity of the geodetic aspects grows significantly as the requested accuracy becomes more demanding. We take into consideration and apply all the appropriate corrections for the divergence between the ellipsoid and geoid surfaces and for the curvature of the vertical (e.g.: height corrections, azimuth corrections, planimetric corrections). Also, the use of astrogeodetic determinations at a number of points serve as a check on theoretical calculations of the deflection of the vertical.

We also investigate the possibility of redefining a best-fit local ellipsoid that minimizes the discrepancies between the geoid and ellipsoid in this local area. The local ellipsoid is suitable in simplifying the process of reducing the terrestrial observations because the deflection of the vertical can be neglected completely. Doing this, however, will introduce a supplementary transformation between the World Geodetic System 1984 (WGS 84) and the local ellipsoid for all the GPS vectors because the GPS systems employ only the WGS 84 datum ellipsoid.

The geodetic measurements in the surface network are performed with state-of-equipment and include: Trimble 4000SSE Geodetic Survey GPS dual frequency receivers, the high-precision electronic distance measurement Kern Mekometer ME5000, precision Kern E2 and Wild T3 theodolites, and precision Kern N3 and Leica N3000 levels.

The machine layout coordinate system is represented by the existing DUSAF local coordinate system. This system never represented an "in situ" map projection with a clear mathematical definition. Consequently, defining the transformation algorithms and parameters between the surveying space and the machine lay-out coordinate system implies the replacement of the old DUSAF system because it no longer satisfies today's levels of required accuracy. The newly defined minimally distorted map projection is an Oblique Mercator, having the origin at a point centrally located and the azimuth of the rotated meridian equal to the actual rotation between the old DUSAF and the geodetic systems and introduces negligible distortions over the project area (at a scale of 1/10,000,000). We are also investigating the possibility of employing a Stereographic projection secant to the ellipsoid at the elevation of the FMI tunnel. Doing this will standardize the scale distortion factor to one for all the surveys performed in the FMI enclosures.

Ten vertical survey shafts will allow us to optically transfer the absolute coordinates from the surface into the tunnel with an accuracy of 0.1 mm. For this task, we will use precise Kern ZN instruments. Deflection of the vertical will be taken into account to correct the planimetric positions of the transferred points. These points transferred inside the enclosure will constitute the reference points to constrain the precise tunnel control micro network. This network will serve as a framework for high-order accuracy positioning of all FMI components.

Comment about our involvement in the construction phase of FMI:
The comparison of the common accuracies of civil engineering with the high precision required for aligning the accelerator components leads us to the conclusion that, at least for the construction phase, the geometry of accelerator must be considered as absolute. The FMI tunnel being strictly dimensioned, its axis must follow the theoretical axis of the machine within tight tolerances. To avoid costly mistakes, it is necessary to establish effective quality control at different stages of the construction and to make final checks of the completed tunnel sections. Thus, the main targets of the Survey, Alignment and Geodesy Group (SAG) for the construction phase of the tunnel will be:

a) to define a close collaboration with the construction firm;
b) to provide the basic geodesic framework defined in the specifications;
c) to limit the risks of errors by preventive operations (i.e. permanent monitoring of constructed elements and quality control checks);
d) to preserve the geometrical conformity of the construction effort.

2. PRECISE "UNDERGROUND NETWORK" SURVEY

Because the beam trajectory is mainly sensitive to short range errors, the major requirement of the FMI geometry is to minimize relative errors. The precision required during the various steps in positioning FMI components requires an underground geodetic network that meets very strict standards and tight tolerances. The assurance of meeting the accuracy requirements can be acquired only with an in depth knowledge of the stochastic behavior of the network.

In order to develop an adequate underground geodetic network and to formulate its stochastic and mathematical models, various criteria (such as accuracy, reliability and expense), need to be balanced in order to optimize the network. Such an optimization process, carried out during the design phase of the network, is classified in four different phases which are referred to as "zero, first, second, and third" order designs. Respectively, these designs relate to the optimal reference system, the configuration of the network and observations plan, the search for an optimal distribution and observation weighting, and to the improvement of the network by including additional points and or observations.

The "zero order" design of the underground network lead us to position ten of the tunnel points underneath the sight risers, representing constraints on azimuth and coordinates. The network will have two constraints to azimuth and ten constraints to coordinates. We will perform two astrogeodetic azimuth determinations, one at MI-60 and the other at MI-30 for confirmation.

The next step in the optimization process was carried out by the "first order" design. The theoretical approach is severely limited by the shape and the geometry of the tunnel which dictates the FMI underground network to be a longitudinal network. The studies carried out lead to a survey framework system based on a chain of 66 braced quadrilaterals. Some of the advantages of the chain of quadrilaterals over other configurations are: the 20% increase of the transmitted azimuth, and the decrease in transversal errors by 15-20%. The base network consisting of 132 monuments will constitute the primary tunnel control network. Each monument position has been chosen to allow observation of at least five other control points from any given monument. On the basis of point distribution, measurements were planned seeking the greatest possible reliability and precision through interactive simulation. This conforms to the characteristic that any geodetic network tend towards homogeneity and isotropy. Restricted by the shape of the network and by instrument limitations, we tried to deal with this constraint by employing the Kern Mekometer ME5000 (st.dev. for distances is 0.2 mm + 0.2 ppm) and a Laser Tracking Interferometer system (st.dev. for angles is 1 arc second, and st.dev. for distances is 1 micron).

We have used extensive "second order" design and reliability criteria to reduce the measurements in a rational manner. This involved only a slight loss in accuracy, but resulted in reduced costs and execution time. Thus, we eliminated the conventional angular measurements in the tunnel which, being time and effort consuming, are plagued by accumulation of lateral refractions and lead to large lateral closure errors. In this resulting trilateration network, starting with the maximum number of possible measurements and constrained by the network redundancy coefficient, we decided not to eliminate the least weighted distance measurements, but chose to replace some of the measurements (made with the ME5000) with ones made by the Laser Tracker, given its superior weighting. We have also analyzed the possibility of measuring the whole network using only the Laser Tracking Interferometer system, given that each quadrilateral is self contained in the instrument's specifications range. The scenario employing only the Laser Tracker allows us to define a less rigid geometric network configuration. This increases the accuracy by one order of magnitude and, according to current estimates, provides a time saving of about 50 %.

In the "third order" optimization design, we added additional diagonal measurements spanning adjacent quadrilaterals to improve the isotropy of the network. This helped to compensate weaknesses caused by the disadvantageous length to width ratio of the braced quadrilaterals.

The points of this primary control network will be fixed and used as the basis of a denser secondary network for beam alignment. This densification network will be developed using the Laser Tracking Interferometer exclusively. The network control points will be located so as to minimize the number of observations necessary for the smoothing routines. They will be positioned close to the beam line, providing monuments for optical tooling setups if necessary. Thus, the primary network will be supplemented with 142 additional points in such a way that each two adjacent points will define a baseline parallel to a quadrupole and located at 2.5 feet off the beam center line.

All the coordinates of the underground network will be computed utilizing three dimensional rigorous least square adjustments. Error propagation analysis indicates that this network should enable us to determine absolute tunnel monument positions to better than ± 0.3 mm and relative component positions to generally better than ± 0.1 mm.

For the points obtained from the surface network in the immediate vicinity of the FMI, the maximum estimated radial standard deviation is ± 0.75 mm. The points transmitted through vertical sight pipes into the tunnel divide the circumference of the ring in 10 sectors. Two of them have a length of 138.310 m (which roughly represents one betatron wavelength). These sectors correspond to the MI-60 and MI-30 straight sections. The other eight sections each have a length of 380.346 m (which represents about three betatron wavelength) and are equally spaced along the rest of the perimeter.

With regard to ONLY the underground geodetic network, which uses these sight pipe points as references, an examination of the error ellipses shows that, after overall adjustment of the circumference, the radial standard deviations are basically similar for each section between sight pipes. They steadily increase from the reference control point, reach a maximum at the middle of the sector and then gradually decrease, disappearing at the next reference point. In each section the pattern of the error ellipses is cigar shaped. The maximum error is represented by a standard deviation of 0.3 mm.

Starting with one tunnel monument as a reference, the error ellipses were calculated for each monument up to those that were diametrically opposite. In this way it was possible to judge the distortion of the reference figure. The value for the semi-major axes of the largest error ellipse is 0.3 mm at the 95% confidence level. The same analysis shows that, from one braced quadrilateral to the next, the variation in the radius of the orbit is of the order of 0.1 mm in relation to the theoretical orbit. Its position in space has a 95% probability of being inside a circle of errors having a 0.6 mm diameter. Within two adjacent quadrilaterals, we aim for the precision in position of the quadrupoles relative to each other to be better than 0.1 mm. Probably, the biggest impediment in achieving this last tolerance are unmodelled systematic measurements errors.

The COMBINED set of radial uncertainties of the surface network and underground framework provides a cigar-shaped envelope for each section. This envelope supplies an overall picture of the possible variations of the accelerator radius which has an uncertainty varying from 1.5 mm (inherited from the surface network) at the reference points to 2.1 mm in the middle of each sector (combined effect surface plus tunnel networks). However, such large mid-section values have no critical influence on the operation of the accelerator provided that the relative radial error remains within the narrow limit of 0.25 mm imposed by the machine's parameters. In meeting this limit of 0.25 mm, the curve of the successive quadrupole positions is compelled to remain continuous with only discrete increments.

The relative errors of quadrupole focusing magnets are the most critical. The radial and vertical variations over distances characterized by the quad to quad spacing and more (up to a betatron wavelength - about 127.669 m) must remain as close as possible to the ideal value given by the theoretical geometry of the accelerator. The next most important aspect is the curve formed by the successive positions of the quadrupoles. It has to be made as smooth as possible along the entire perimeter of the machine. Thus, our two basic concerns are: first to carry out an overall alignment that positions components as close to the theoretical geometry as possible, and, second, to smooth the curve in order to minimize the errors locally.

UNDERGROUND MONUMENTATION

The underground reference control system is represented by 208 control points permanently imbedded in the tunnel floor and 66 control points rigidly attached to wall brackets. The actual monuments are represented by spherical reflectors whose centers define the control point coordinates in all three dimensions. To obtain high accuracy in the underground geodetic system, we will use high-precision type reference sockets for centering and holding the Laser Tracking Interferometer's reflectors.

FIDUCIALIZATION

The fiducialization of the components relates their effective magnetic centerlines to external mechanical points that are accessible to subsequent survey measurements. The coordinates of the fiducials on each magnet will be defined with respect to the local coordinate system of the magnet, in the beam direction.

At present we propose to utilize magnet fixtures carrying two reference fiducials. The three point fixture clamps at each end of the magnet to grooves whose locations relative to the magnetic centerline of each magnet is well known. This non deformable assembly will carry two fixed sockets which will hold 1.5 inch reflectors for providing Laser Tracking Interferometer measurements. The fixtures will be calibrated on a regularly schedule routine. The repeatability of these fixtures will be known and documented.

The magnets will be fitted with fiducial points and the coordinates of these fiducials will have to be determined in a three dimensional coordinate system. A set of datum surfaces, corresponding with the physical surfaces of each type of magnet, will be established as mechanical references for all fiducials. The three dimensional mechanical locations of the fiducials will be determined in the local coordinate system of each magnet with its origin at the geometric center of the magnet. Nominal values determined by the magnet design dimensions and geometry will be used in these calculations.

Since the construction errors are non-systematic, the shift in the location of the magnetic versus the mechanical center must be tested and eventual corrections of the fiducial data must be made.

Using the beam lattice that defines component locations, the coordinates of the fiducials will be transformed from the local coordinate system of the magnet into the beam coordinate system.

3. COMPONENT INSTALLATION ALIGNMENT

For running the FMI accelerator it is of great importance to have good alignment for each component. Each magnet will be clearly defined by six degrees of freedom. Especially important are the radial and vertical positions of the quadrupoles and dipoles. The maximum one sigma deviation of the alignment errors with respect of these degrees of freedom is 0.25 mm for the quadrupoles. For dipole magnets, the most significant consideration is the roll angle and the standard deviation of its alignment errors is not to exceed a value of 0.5 mr.
With the knowledge of the three dimensional coordinates of the underground control points and the complete understanding of the errors associated with them, we can proceed to the alignment of the components.

The alignment tolerance specifications distinguish between absolute and relative positioning. The absolute positioning tolerance defines a maximum global shape distortion by specifying how closely a component has to be placed on its ideal location. The most important tolerance, the relative positioning tolerance, defines the alignment quality of adjacent components.

Consequently, we propose to align FMI components by the following procedure which underlines two major steps and provides the transition from the absolute to relative positioning.

3.1. Absolute positioning
For the absolute positioning task, the following alignment cycle is proposed:

3.1.1. Installation of the magnets stands.
In preparation for the installation of the support system, a survey will be performed to lay out the anchor bolt positions. This will be done from the tunnel control points with an accuracy of ±3 mm. After the survey, the stands will be installed with their adjustment systems set at mid range for horizontal displacements and 1 cm higher for vertical displacements. Each stand has six adjustment screws to enable movements in three directions (translation) and movements through three angles (rotations), corresponding to the six degrees of freedom of all magnets.

3.1.2. Installation of the magnets.
To correct the position of the magnets according to the results of the measurement, they have to be installed rigidly on three point stands. This requires that the mechanical design of the stand or frame must preclude any kind of non elastic deformations.

3.1.3. Alignment of the components.
The search for accuracy in geodetic metrology for accelerator alignment also demands improvements in technical and economical efficiency of instrumentation, in field measurement procedures, in data logging, in data processing and in data management.

To align the magnets, it is necessary to measure and calculate the three dimensional position of their fiducials, and then to correct the transverse, vertical and longitudinal offsets of these reference marks with respect to their position in the beam as given by the lattice defining component location. To correct the magnets to their theoretical position by a calculated amount, the adjustments of the stand supporting the magnets will be used. A digital, electronic inclinometer will be used to control the roll inclination of the components. This third step will be iterated until the proper alignment is achieved, keeping in mind that the accuracy of this positioning process is a function of the mechanical resolution of the supporting stands. After installing all the accelerator components, the actual coordinates of the fiducial points on the magnets will be computed. These actual coordinates will be compared with the nominal values and the difference coordinate vectors will be determined.

As instrumentation we propose to employ the Laser Tracking Interferometer system. All the FMI magnets will be positioned using an interactive and iterative procedure from the layout of coordinates for the magnet support systems to the final smoothing of adjacent components. The automation of measurements and alignment procedures significantly improves their quality compared to that of traditional methods.

The Laser Tracking Interferometer is a highly dynamic measuring system for three dimensional coordinate determination using a single beam laser interferometer, precise angular encoders and a sophisticated servo-tracking system. Simultaneous readings, 1000 times per second, of horizontal and vertical encoders and interferometer counts are calculated *permanently* and the three dimensional position of the reflector target is displayed in real time. These coordinates are continuously compared with the theoretical coordinates and the resulting difference coordinate vector is also displayed in real time. For 10 micron interferometer resolution and 1 arc second (possibly 1/2 arc second) angular resolution of the Laser Tracker, we estimate to provide measurements to the magnet fiducials within 0.1 mm range. This automatic transmission and handling of measurements and alignment parameters entirely excludes the usual risks of operational errors during routine work.

3.2. Relative positioning

When installing the machine components, the first determination of the magnet fiducials coordinates will give the displacement vectors between their actual "rough" position and their theoretical one. The accuracy obtained in the absolute positioning step is the quadratic sum of many random factors (surface network, transfer of control through penetration shafts, tunnel control, magnet fiducialization, magnet lay-out, etc.) plus the linear sum of any residual systematic errors (instruments calibration, forced centering, velocity correction of light, horizontal and vertical refraction, etc.). The statistical nature of the final relative errors, which are a quadratic combination of those of the network itself and those of the positioning and installation process, is essentially Gaussian. Therefore, random errors generated during components alignment are normally distributed around a mean curve, as are the components.

This unknown trend curve (one among infinity), around which the magnets will be positioned, is contained, in a random manner, inside the envelope of maximum errors of 2.1 mm. The typical error envelope for the absolute alignment is cigar-shaped, the measured components reference line oscillating somewhere within this envelope. The definition and the degree of the curve depends on redundancy, on the distance between reference control fixed points, on overlap of the measurements, etc.

If the positions of the magnets diverge from the nominal positions in a systematic manner, the running of the FMI accelerator will not be affected. Therefore, it will only be necessary to have a high accuracy in the immediate vicinity of components. If adjacent magnets are positioned on the smoothing curve, systematic deviations from nominal and actual positions will not be important as long as systematic deviations do not follow a sinusoidal function, the frequency of which is near the betatron-frequency or its multiples.

In fact, the magnets will not be positioned on the smooth curve exactly. They will deviate more or less, these deviations determining the quality of the alignment. The systematic part of the quality coefficient represents the remaining significant deviations, while the random parts will be determined by the accuracy of the measurements and will be described by the relative error ellipses or by the relative accuracy of the radial and vertical position components.

For the relative positioning task, the following alignment cycle is proposed:

3.2.1. Systematic parts, which are included in the components radial and vertical differences have to be calculated by means of interpolating functions (polynomials, Fourier series, spline functions, etc.), producing a smoothing curve. On the basis of the smoothing results, the values of the radial deviation parameters of each quadrupole will be calculated.

A very important consideration is that, when making surveys of long and flexible figures, the resulting trend curves must be analytically evaluated for not introducing, or for eliminating, systematic or harmonic errors which are critical for the accelerator. Therefore, special smoothing algorithms have to be developed in order to process the local data in a purely relative way.

As general criteria, the smoothing algorithm has to be defined by four major goals:

a) to simultaneously model errors for both horizontal and vertical directions;
b) the curve's shape to be suggested by the data and not by a predetermined model;
c) the curve must be a reproducible fit, independent of the inconsistent nature of the human judgment;
d) the result of the procedure is to minimize the number and the size of the magnet movements to reach the final alignment criteria.

The purpose of smoothing is to model, or remove, errors. These errors can be regarded as a second set of data that has been added to our "correct" set of data. Generally, the errors vary in a somewhat random fashion at high frequencies. However, in the case where errors are introduced by instrumentation and human bias, the errors usually vary at low frequencies. The smoothing filters out data that varies at frequencies lower, or higher, than the frequencies expected to exist.

The trajectory of the beam within such long and flexible ring-shaped figures, with variations of coordinates issued from different sets of comparable measurements, is mainly sensitive to short-range errors, the long-range errors having less effect but not being negligible.

The FMI absolute design path of the beam is a series of straight sections and compound curves. The complication of the irregularly shaped beam line may be eliminated by subtracting out the actual size and shape of the beam line and leaving a series of residual misplacements for a string of magnets (uncoiling the ring). A series of transformation programs should standardize the measured magnet misalignments to a common reference line where they can be modeled.

The mathematical method is not trivial and different methods are presently being tested and evaluated for separation of absolute and relative discrepancies. Being aware of the weaknesses of some of those functions (i.e., low order polynomials do not model the short wave length behavior of the curve well enough, high order polynomials generate inner constrains between data points and tend to create sine wave type resonance oscillations, the Fourier functions determined by spectral analysis or Fourier decomposition is dangerous with respect to the harmonic sensitivity to beam orbits), we focus our efforts in searching for a more sophisticated and reliable smoothing process.

The spline function approach will be considered as a possible solution if further simulations certify that the path of the beam can be fitted with splines. Another approach to be tested is to use Principal curve analysis to simultaneously pass a non-parametric curve, with its shape suggested by the data, through the horizontal and vertical residuals misalignments mapped along the beam axis. The smoothing routine will also include robustness estimators in the modeling program to weight out the points and detect outliers from the trend curve.

3.2.2 Each magnet will be moved only by the difference between the component's radial/vertical deviations and the values of the interpolating function at that place. The eventually small displacements required as a result of the calculations will be performed with the adjustment screws on the support stands.

This cycle will be iterated until the differences from step 3.2.2. are so small that the quality coefficient of the alignment and the additional conditions are obtained. After the smoothing is carried out, the distribution of residuals needs to be examined by Fourier decomposition type analysis to ensure that no significant amplitudes occur at the betatron frequency.

The detailed analysis of the survey monuments and radial smoothing results based on the RMS. sum of all the random deviations on the radial position of the quadrupoles gives us information about the quality of the alignment.

4. ERROR ANALYSIS OF MAGNET ALIGNMENT

Along one betatron wavelength, FMI accelerator physics requires a one sigma deviation of 0.25 mm in alignment errors with the radial and vertical positions of quadrupoles and the roll angles of dipoles being especially important. It will be necessary to have high accuracy only in the neighborhood characterized by the quad to quad spacing. The operation of the accelerator will not be significantly affected if the positions of the magnets diverge from the nominal positions in a systematic manner, the systematic errors being modeled by the smoothing procedure. Analysis of the magnet alignment budget emphasizes the individual contribution of alignment component errors and assigns their allowable magnitude.

There are four characteristic alignment component errors which independently affect the total radial standard deviation of a magnet alignment:

$$\sigma = \sqrt{\sigma n^2 + \sigma m^2 + \sigma f^2 + \sigma s^2}$$

where:

σn = the standard deviation of the errors in the network (the relative transversal errors between control points)

σm = the standard deviation of the errors of the measurements from control points to fiducials

σf = the standard deviation of the errors between fiducials and magnet centers

σs = the standard deviation of the errors resulting from adjusting the support stands.

In the processes of analyzing the individual alignment errors and of allocating them proper tolerances, we employed two criteria: the principle of equal influence of independent sources of errors, and the principle of differential influences of component errors.

In order to confirm the estimated standard deviations of the underground network, various simulations of the whole tunnel network have been carried out. The error propagation analysis of the network simulations has shown that the radial component of relative position error between adjacent points is better than 0.1 mm. Moreover, even over a betatron wavelength, we have not seen fluctuations in radial relative errors in position between control points that exceed 0.15 mm.

As a check on the estimated standard deviation of the measurements from the points to fiducials, we performed various simulations of magnet